Development and Deployment of an Extreme Turbulence (ET) Probe for Hurricane and High-Wind Research

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LONG-TERM GOALS

Turbulence plays an important role both in the development of tropical cyclones and in the property damage associated with such storms. Turbulent exchanges of heat and momentum between the atmosphere and the underlying surface are a primary driving factor in the intensification and decline of tropical cyclones. The damage patterns created by tropical cyclones at landfall are often associated with peak turbulent wind gusts and not just the sustained winds. Few in-situ observations of turbulence and surface fluxes have been made in the extreme environment associated with these tropical systems. Most research-grade turbulence instruments are not designed to function in hurricane-force winds, and they work poorly in heavy rain. An Extreme Turbulence (ET) probe is being developed to measure near-surface winds, turbulence, and fluxes in the high winds and precipitation rates encountered in tropical cyclones. This probe also has potential uses in other storms capable of producing high winds.

OBJECTIVES

The objectives of this project are:

1. To design, build, and test an ET probe suitable for measuring winds and turbulence in the extreme conditions found within tropical cyclones or other storms associated with hurricane-force winds
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14. ABSTRACT
Turbulence plays an important role both in the development of tropical cyclones and in the property damage associated with such storms. Turbulent exchanges of heat and momentum between the atmosphere and the underlying surface are a primary driving factor in the intensification and decline of tropical cyclones. The damage patterns created by tropical cyclones at landfall are often associated with peak turbulent wind gusts and not just the sustained winds. Few in-situ observations of turbulence and surface fluxes have been made in the extreme environment associated with these tropical systems. Most research-grade turbulence instruments are not designed to function in hurricane-force winds, and they work poorly in heavy rain. An Extreme Turbulence (ET) probe is being developed to measure near-surface winds, turbulence, and fluxes in the high winds and precipitation rates encountered in tropical cyclones. This probe also has potential uses in other storms capable of producing high winds.

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2. To deploy ET probes in the path of landfalling tropical cyclones to observe changes in winds, turbulence and surface fluxes as the storms move inland.

3. To collaborate with other scientists in deploying ET probes in high-wind conditions.

These objectives fit into the overall goals of both the ONR Coupled Boundary Layers Air-Sea Transfer (CBLAST) initiative and the Hurricane at Landfall initiative sponsored by the U. S. Weather Research Program.

APPROACH

The project has developed a relatively low-cost, robust probe that can measure turbulent fluctuations in the high winds (> 30 m s^{-1}), heavy rain, and spray associated with strong tropical cyclones. The NOAA Air Resources Laboratory (ARL) has for many years used pressure-sphere anemometers (Brown et al. 1983; Crawford and Dobosy 1992) to measure turbulence quantities from fixed-wing aircraft. These devices, which have no moving parts, use pressure sensors connected to an array of ports on a spherical surface. The observed pressure distribution over the spherical surface is used to compute the magnitude and direction of the incident airflow. In aircraft applications, these anemometers are routinely operated at airspeeds of 50-60 m s^{-1} or higher, which correspond to at least a category 3 hurricane on the Saffir-Simpson scale.

An aircraft probe requires only a partial sphere containing a few pressure ports pointing forward. A ground-based probe needs to be omnidirectional, so a full sphere with ports evenly spaced around the equator is required. The Extreme Turbulence (ET) probe developed at ARL is designed around a 43 cm diameter spherical shell made from fiberglass-epoxy composite. Ten pressure ports are located on the sphere's equator at 36° intervals. Two other rows of ports are located 18º above and below the equator. In all, the probe has 30 ports connected to 20 differential pressure sensors and 6 absolute pressure sensors. Additionally, two temperature sensors are located in a small housing on top of the sphere.

Data from the ET probe are collected by a nearby computer. Raw pressure and temperature data are first digitized at 50 Hz. The processing software then uses the pressure data to search for the location of the wind stagnation point on the sphere. Data from the pressure sensors closest to the stagnation point are used to compute a 50 Hz time series of the ambient wind vector. If required, the processing software can also include algorithms for filtering out the effects of rain and spray on the pressure data. In the longer term, the system may include a satellite link or other wireless transmission technology to send data to a remote location out of harm's way.

Once prototypes of the ET probe were completed and tested, they were deployed near the coast in the path of landfalling tropical cyclones. These deployments were in collaboration with other scientific teams, as coordinated through the Hurricane Research Division of the NOAA Atlantic Oceanographic and Meteorological Laboratory.

WORK COMPLETED

Fiscal Year 2005 is the last year of CBLAST funding for the ET probe. The total ONR funding in this final year was insufficient for any field deployments during the 2005 hurricane season. Instead, the limited funding was directed at analyzing the data collected during the highly successful 2004 season and at publishing papers describing the ET probe development and deployments.

By the end of September 2004, ARL had completed two successful deployments of ET probes into Hurricanes Frances and Ivan. In total, these deployments generated over 80 hours of wind and turbulence data covering the periods of the hurricanes' landfalls. Initial results obtained from the raw data were highly encouraging, but the more detailed quality analysis and postprocessing of the data did not start until FY 2005. A series of quality assurance procedures were developed to identify periods when the observations are either obviously bad or questionable. These periods are identified by a series of nine quality flags that are associated with the data. After completion of the quality assurance procedures, the final processed data were stored in NetCDF format together with the quality flags and a large set of metadata. The NetCDF files are designed to be self-describing, so that researchers can access and use the data without requiring ancillary documents to describe the file contents. The postprocessing and archiving of all the data from both hurricanes was completed by January 2005.

The remaining 2005 funding, including contributions from NOAA, was devoted to writing manuscripts based on the ET probe work at ARL. Currently, the plan is to write and submit two manuscripts: one describing the design of the probes and a second on the hurricane data collected in 2004. The first of these manuscripts, entitled “A Pressure-sphere Anemometer for Measuring Turbulence and Fluxes in Hurricanes”, was nearing completion at the end of FY 2005, and is expected to be submitted to the *Journal of Atmospheric and Oceanic Technology* shortly. Work on the second manuscript will begin thereafter. Since this is the last year of CBLAST funding, the final publication of these papers will be funded through NOAA.

Overall, we feel that ARL has been highly successful in meeting the objectives set out at the start of the ET probe program. Starting from a theoretical concept five years ago, ARL has succeeded in developing a real probe capable of collecting wind and turbulence data in hurricane conditions, and was able to deploy the probes into landfalling hurricanes during the 2003 and 2004 hurricane seasons. The initial work accomplished through the CBLAST program has provided the groundwork for further developments and applications the of ET probe to support research related to tropical cyclones and other storms.

RESULTS

The postprocessing of the data from Hurricanes Frances and Ivan indicates that the data collected are of high quality. Only rarely did the wind data from the probes show any evidence of rain spikes, indicating that the use of large-diameter pressure ports and upward-sloped tubing was largely successful in keeping the pressure ports from being fouled by water. The only periods when the wind data showed a larger percentage of errors were when the wind speeds fell below the lower threshold (5-8 m/s) required for proper operation of the probes. These periods are of little interest for hurricane research, since they occurred either early in the deployments when the hurricane was still far out to sea or at the end of the deployments when the storms had moved away from the probes.

Figure 1 provides an example of the turbulence data collected with the ET probes during the landfall of Hurricane Ivan. It shows the variation of the turbulent kinetic energy (TKE) during a 30 hour period centered near the time of landfall. The probe was deployed at a Naval airfield called NOLF Wolf, which is near the Alabama Coast just west of Pensacola, FL. Over the course of the storm, the TK increased by a factor of ten, with a peak value of about 30 m^2s^{-2}. Such TKE data are potentially useful for structural engineering applications, since it provides information about the structural wind loads that are associated with turbulent gusts in hurricanes .

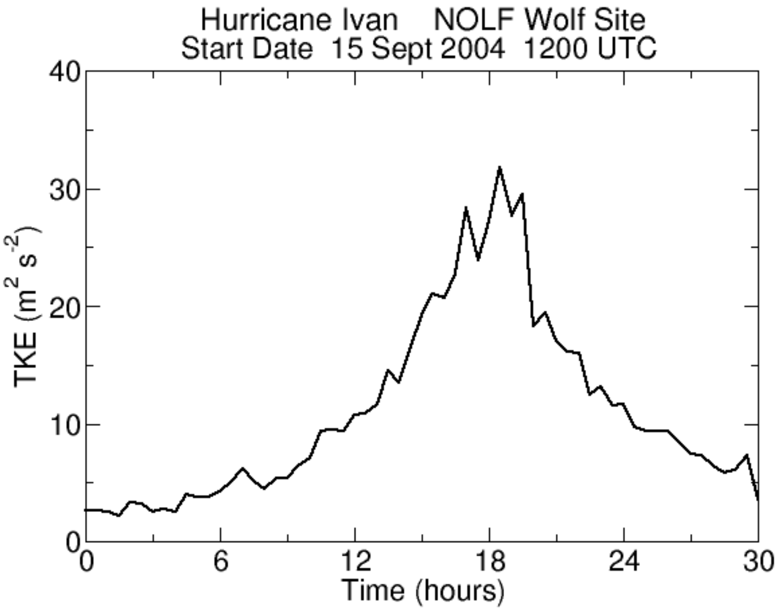

Fig. 1: Turbulent kinetic energy observed during Hurricane Ivan, showing a ten-fold increase at the peak of the storm.

The ET probes are also capable of measuring vertical fluxes, particularly the momentum flux, which is often normalized in the form of a drag coefficient C_d. Fig. 2 shows a plot of C_d for the same time period as in Fig. 1. Except for some scatter early in the deployment when the winds were light, the drag coefficient is nearly steady at about 5.0×10^{-3}, which is reasonable given the land location of the probe. The value of C_d over the ocean in high winds is currently an issue of significant debate (e.g., Powell et al. 2003), and the ET probes have the potential of providing in-situ observations under these extreme conditions.

IMPACT/APPLICATIONS

The successful development of the ET probe fulfills a need for turbulence and air-sea interaction data under high wind conditions and heavy rain. Standard research-grade turbulence instruments do not meet this need. The lack of air-surface exchange data in high winds is an important source of uncertainty in tropical cyclone modeling, particularly the variation of drag coefficients at high wind speeds. There is also interest in using ET probes for structural engineering applications, since the probes can measure turbulent wind fluctuations that are of importance for structural wind loads. ET probes have potential applications to other atmospheric phenomena involving high winds, including strong extratropical cyclones.

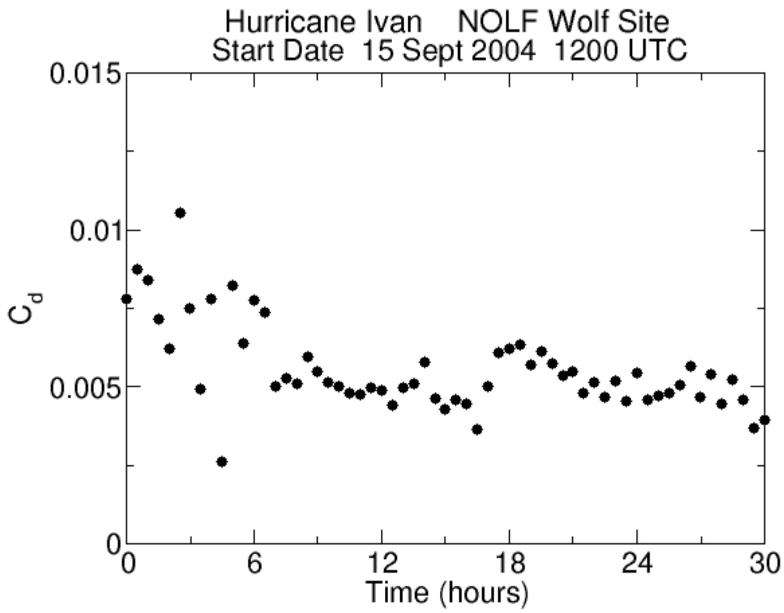

Fig. 2: Observed drag coefficient during Hurricane Ivan, showing a near-constant value of 5×10^{-3}, as expected for a land location.

TRANSITIONS

After the successful deployments in 2004, NOAA has shown interest in deploying ET probes for both hurricane research and possible transitions to operations. Requests are currently in the FY 2008 NOAA budget for these activities. It is possible that NOAA may fund this work earlier through hurricane supplemental funding. The overall intent of these requests is to add ET probes to existing NOAA operational platforms, including C-MAN coastal stations, moored buoys, and possibly some of the coastal sites operated as part of the Climate Reference Network.

RELATED PROJECTS

The Air Resources Laboratory has one other CBLAST project that involves anemometer technology similar to the ET probes. The CBLAST-Hurricane project (http://www.noaa.inel.gov/projects/cblast-hurricane/) has installed a pressure-sphere anemometer on one of the NOAA WP-3D hurricane-hunter aircraft. This system was successfully tested in hurricanes during the 2003 and 2004 hurricane seasons. The ARL hurricane deployments have also been closely coordinated with the activities of the Texas Tech Hurricane Intercept Team (http://www.atmo.ttu.edu), which deploys more conventional tower instrumentation in hurricanes. During all the ARL deployments, the ET probes were co-located with Texas Tech towers.

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